AFRL-SR-BL-TR-98-

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE 6 January 1998	3. REPORT TYPE AND DATES COVERED Final technical report (11/1/93 - 10/31/97)

4. TITLE AND SUBTITLE
Hydroacoustic arrays for seismic detection, location and discrimination: A comparison with land-based seismic arrays and networks

5. FUNDING NUMBERS

grant F49620-94-1-0041

6. AUTHOR(S)

Donna K. Blackman and John A. Orcutt

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of California, San Diego
Scripps Institution of Oceanography
IGPP (0225)
La Jolla, CA 92093

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/PKA
110 Duncan Avenue, Room B115
Bolling AFB, DC 20332-8080

10. SPONSORING /MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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DTIC QUALITY INSPECTED 2

14. SUBJECT TERMS

SOSUS, T-phases, hydroacoustic recordings, NORESS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT unclassified	20. LIMITATION OF ABSTRACT SAR

19980129 060

Seismoacoustic Studies of the Norwegian Sea

Donna K. Blackman and John A. Orcutt
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography, La Jolla CA 92093-0225

Objective.

U.S. Navy hydrophone arrays (SOSUS) record signals in a range of frequencies that includes earthquake and explosive sources as well as those relevant to submarine detection, for which they were designed. In the Norwegian Sea we compared recordings of acoustic arrivals on SOSUS with seismic recordings at the arrays on land in Norway. We also studied seismic activity along the spreading centers between Iceland and Svalbard in an attempt to discern any difference in levels of seismicity associated with different sections of the ridge system.

The Norwegian Sea offers a unique setting for assessing SOSUS use for seismology due to the existing combination of seismic activity, instrumentation and varied physiographic conditions (Figure 1). The different seismic sources in the region provide a range of signal types and locations (e.g. Vogt, 1986): large oceanic earthquakes from transform faults along the plate boundary between Iceland and Svalbard; smaller oceanic earthquakes associated with volcanic eruptions along the rifting portion of the plate boundary; mining explosions on land; slope failure events on the continental shelf. Several types of recordings of Norwegian Sea seismic activity are available from instruments whose capabilities dovetail each other: the Global Seismic Network (GSN); the seismometer arrays in Norway and on Spitsbergen; and the SOSUS acoustic arrays.

This project was envisioned as a fundamental inquiry into the nature of a very important oceanic regional phase that had not been studied with the tools of modern seismology, the T-wave. Through a combination of synthetic studies and the collection of both oceanic and continental data for specific events, we proposed to study not only the excitation and propagation of T-phases, but the use of the information in T-phases for determining source parameters. The new availability of previously classified seafloor hydrophone data (Navy SOSUS) coupled with the several land seismic arrays (NORESS, ARCESS, and Spitsbergen) provided a unique opportunity to study this problem in the Norwegian Sea.

Approach.

We compared oceanic hydroacoustic recordings of earthquakes with data collected at the Norwegian seismic arrays and the Global Seismic Network (GSN). In order to obtain a statistically significant database, a three year study was proposed. Unfortunately, a combination of technical, security and budget issues resulted in delays in the start up, and the subsequent shutdown, of the SOSUS archive after only 18 months of recording. None-the-less, for the Nov95-Sep96 period, we obtained a great deal of useful data and we have been able to make progress on several aspects of our initial list of goals:

- Collect parameter data from seismic events in the Norwegian Sea and within 50 km of the coastline. A database was developed for GSN, Norwegian array, and SOSUS data for the study area.

- For activity associated with a volcanic swarm on the Mohns Ridge, improve epicenter estimates by using a land-derived master event location and SOSUS arrival times to constrain relative shifts in event locations.

- Examine biases in seismically-derived event locations to improve the use of the onshore array algorithms for ocean basin events.

- Examine the spatial and temporal patterns of ridge earthquakes for implications for spreading center mechanisms and systematics.

- Assess the relative detection levels and location accuracies in the Norwegian Sea for the seismic and acoustic data sets.

Seismic Results (GSN & Norwegian Array Data).

Analysis of 27 months of data from 1989 to 1992 suggested that several event locations determined by the Intelligent Monitoring System (IMS) at the Center for Seismic Studies (which evolved into the Center for Monitoring Research (CMR)) may have reflected the location that the T-phase was converted to seismic energy at the slope. Out of 371 events listed from the IMS for the 89-92 period, 16% were located along the steep slope of the eastern Norwegian Sea basin. Five of these slope events off Spitsbergen were co-detected by the GSN and listed in the USGS Preliminary Determination of Epicenters (PDE) but with locations on the Knipovich spreading center. This indicates that acoustic energy from sources in the basin interior can propagate some distance in the ocean before coupling into seismic waves at the continental slope. Apparently the amplitude of these converted phases was large enough to influence the determination of epicenters by the IMS during the 89-92 period.

There were significant differences between the source locations and times for many codetected events in the Norwegian Sea between 1990 and 1993. The median size of the location misfit was 40-50 km for 1990-1992, and 30 km for 1993. The average disagreement in estimated source time was 4-5 seconds throughout the (pre-94) period although the variance of the misfit decreases from 12 seconds in 1991 to 5 seconds in 1993. About 80% of the 1990-1992 IMS source times are later than the PDE source times; in 1993, virtually all are later. Most of the IMS epicenters are east or southeast of the PDE epicenters. There is improved agreement between the epicenters in 1993 which suggests that the addition of the Spitsbergen array was quite important.

Figure 1 shows the distribution of earthquakes listed by CMR as well as those listed in the PDE for a more recent period. Between November, 1995, and May, 1996, CMR lists 171 events, PDE lists 75 events and 54 events are listed by both bulletins. There does not appear to be a consistent pattern in the 28% of events listed in the PDE that are not listed by CMR. The magnitude estimates and locations differ somewhat between the bulletins for co-listed events in this time period. On average, their epicenters match to within about 20 km although two events have a PDE location more than 100 km from the CMR location.

The Center for Monitoring Research provided subscription service throughout the study so that daily reports of seismic activity in the Norwegian Sea were sent via email. This information provided an ongoing view of moderate magnitude events and highlighted periods that we should investigate in more detail through combined analysis of the seismic and SOSUS data.

Initial Work with SOSUS Data.

The link to the Norwegian Sea SOSUS system was established in February, 1995, through the efforts of Dr. Clyde Nishimura, our colleague at the Naval Research Laboratory in Washington D.C. Data began to accrue immediately for 15 of the 16 channels that the archive system could accommodate. The first 8 months of data were of moderately useful quality allowing us to address some initial goals. We were not able to monitor individual hydrophones due to missing wiring diagrams at the site so our initial plan to devote half the archive channels to single phones was modified. The recording system was upgraded in November 1995 and the site was shut down by October 1996 so we have 11 months of fully useful beam-formed hydrophone data. We monitored pre-formed beams (processed using the U.S. Navy beamforming parameters) from more than one array location. We decided to focus our initial efforts on the Mohns Ridge, a known source of frequent, low-level seismic activity, so the choice of beams to archive was made accordingly.

The hydrophone array locations are classified so data were processed at the secure facility at NRL (the Dual Use Analysis Center was designed to accommodate scientific research using SOSUS data (Nishimura and Conlon, 1994)). The archive tapes were sent from Keflavik to NRL at 3-4 week intervals, each tape containing 2-3 days worth of 16-channel data. The sampling rate was well above that required for seismic research since marine mammal research is carried out with the same data. In May 1995, tapes for the first 5 weeks of the archive were available so these data were downloaded and the number and types of acoustic arrivals recorded on the various channels was catalogued for a continuous 36-day period. Subsequently, the corresponding CMR and QED (U.S. Geological Survey's Quarterly Epicenter Determination) bulletins were consulted in order to assess which acoustic events were likely to be regional or teleseismic arrivals.

Events recorded for the 36-day period could be classified in three categories reflecting source region: southern Mohns ridge; northern Mohns ridge; more distant regional or teleseismic events. The events were only generally located based on which beams showed a signal, which did not, and what the relative amplitude of the arrivals was between beams with signal. Almost a hundred T-phases emanating from the southern Mohns ridge were recorded, 11 had a preceding P-phase with short duration and lower frequency content. The T-phases varied in amplitude, spectral content and duration. Just over two dozen T-phases were recorded from the northern Mohns ridge area, only one of which had a clear P-wave preceding it. All channels recorded 28 events, 6 of which were preceded by probable P-wave energy. Based on the CMR listings for this time period, at least two of these all-channel events corresponded to known regional earthquakes: a 4.1 mb on the Kolbeinsey ridge and a 2.3 ML on the Knipovich ridge.

The SOSUS arrays record both regional T-waves and teleseismic body waves. An example of a teleseismic P arrival from the 27May95 Sakhalin earthquake (7.6 Ms, range 55° from Jan Mayen Island) is shown in Figure 2. This arrival can be seen in the raw beam data but filtering significantly improves the signal-to-noise ratio for the 1-4 Hz frequency range. An example SOSUS recording of a 3.7 mb event on the Kolbeinsey Ridge is also shown in Figure 2.

The Mohns Ridge Earthquake Swarm: Seismoacoustic Analyses.

A swarm of earthquakes on the Mohns Ridge began November, 1995, and was listed by CMR in the Reviewed Events Bulletin. Earthquake activity detected by the onshore arrays was mainly concentrated in a 2-week period and event magnitudes ranged from 3.5 to 4.8 m_b (Figure 3a). During the subsequent year, several isolated events were also reported from the area.

Analysis of SOSUS data for this period shows that over 7000 events occurred during the earthquake swarm (Figure 3b). Recorded arrivals include P-waves, water-borne T-waves, PT pairs and P-waves reflected at the seasurface. Activity started before mid-November, 1995, (we cannot document the start precisely due to a recording problem at the time) and continues into January, 1996. The greatest number of events (> 40/hr) occurred over a 3-day period in the middle of the 70-day duration of the activity.

Separation in time of P- and T-waves recorded at the SOSUS arrays was used to determine relative locations of events and their spatial evolution throughout the swarm. A land-array-derived epicenter was used as a master event and SOSUS-derived relative shifts were simply projected along the trend of the ridge axis. The locus of activity shifts by 30-40 km (Figure 3c) during the swarm but no apparent steady migration of activity is seen in contrast, for example, with the migration of seismicity observed in Iceland during an eruption of Krafla (Einarsson and Brandsdottir, 1980). This suggests that surface breaks during dike injection did not occur or, at least, did not generate T-waves or that the swarm was not associated with a simple dike emplacement along the ridge.

CMR listed swarm epicenters extending as much as 100 km down the flank of Mohns ridge. Analysis of the T-P separation times indicates that the events must have occurred within at least 50

km of the ridge axis. Also, the PDE places the epicenter located furthest off axis by CMR as being much closer to the ridge axis (Figure 1 shows a line connecting the two estimates).

The temporal pattern of seismicity during the swarm is quite similar to that observed for two known volcanic events that recently occurred on spreading centers in the northeast Pacific (Fox et al., 1993; NOAA VENTS web page). The slower spreading rate of the Mohns ridge may play a role in the fact that the activity lasts about twice as long as has been the case at the intermediate-spreading NE Pacific eruptions. A current or very recent volcanic eruption has not previously been documented along a slow-spreading mid-ocean ridge so these data provide a first look at the nature of such episodic plate spreading and accretion processes.

For the purposes of monitoring a CTBT, these Mohns Ridge data provide a quantitative picture of the types of acoustic arrivals associated with a swarm of small earthquakes that probably correspond to a volcanic eruption. This type of seismoacoustic activity could occur along any of the slow-spreading ridges (eg. the Mid-Atlantic Ridge or the Southeast or Southwest Indian Ridges).

Conclusions.

Combined use of SOSUS hydrophone data and seismic data from the land arrays definitely improved our ability to characterize events in the Norwegian Sea. For small events along the spreading centers, the SOSUS archive contained 2-3 orders of magnitude more events than were listed by CMR. The signals associated with volcanic activity along the spreading center (which could differ notably from the type of activity that occurs at large, isolated seamounts in the Pacific) are variable in their frequency content and duration. It is perhaps this range in signals (from impulsive body wave arrivals to more drawn out T-waves that lack strong energy in the 1-2 Hz range but may extend beyond 50Hz in their higher amplitude spectral peaks) together with the time history of the events in a sequence (Figure 3) that is most indicative of a volcanic source.

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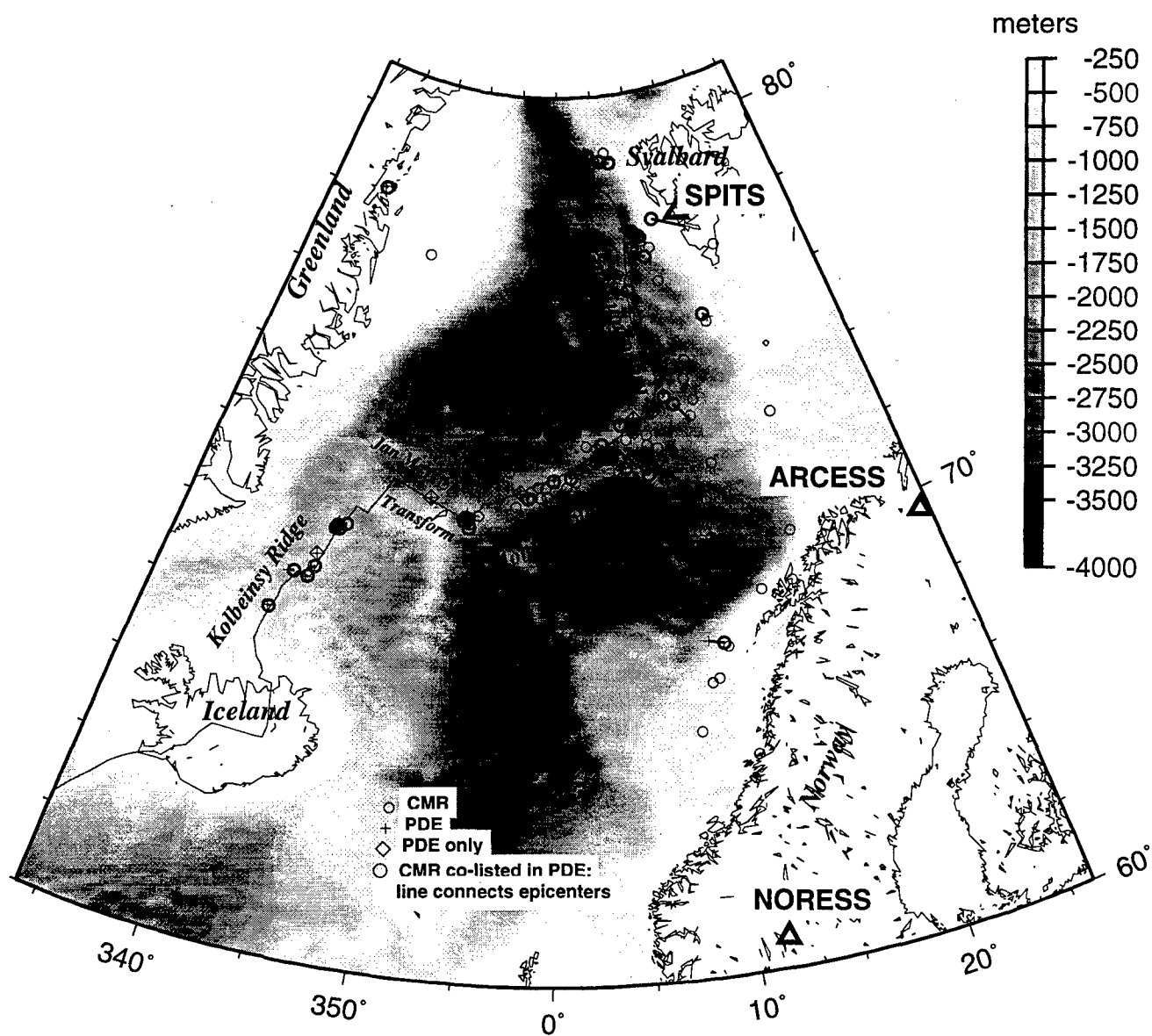
Figure 1. Tectonic setting and recent seismicity of the Norwegian Sea study area. Shading depicts bathymetry which highlights the spreading centers and basin geometries. Solid line marks the plate boundary, as labeled; onshore seismic arrays are indicated by triangles. Epicenters are shown for the period Nov95-May96 as listed by the two bulletins: CMR is Center for Monitoring Research's Reviewed Events Bulletin; PDE is the USGS Preliminary Determination of Epicenters. Epicenters for events listed in both bulletins are shown by double-lined circle connected to + by heavy line.
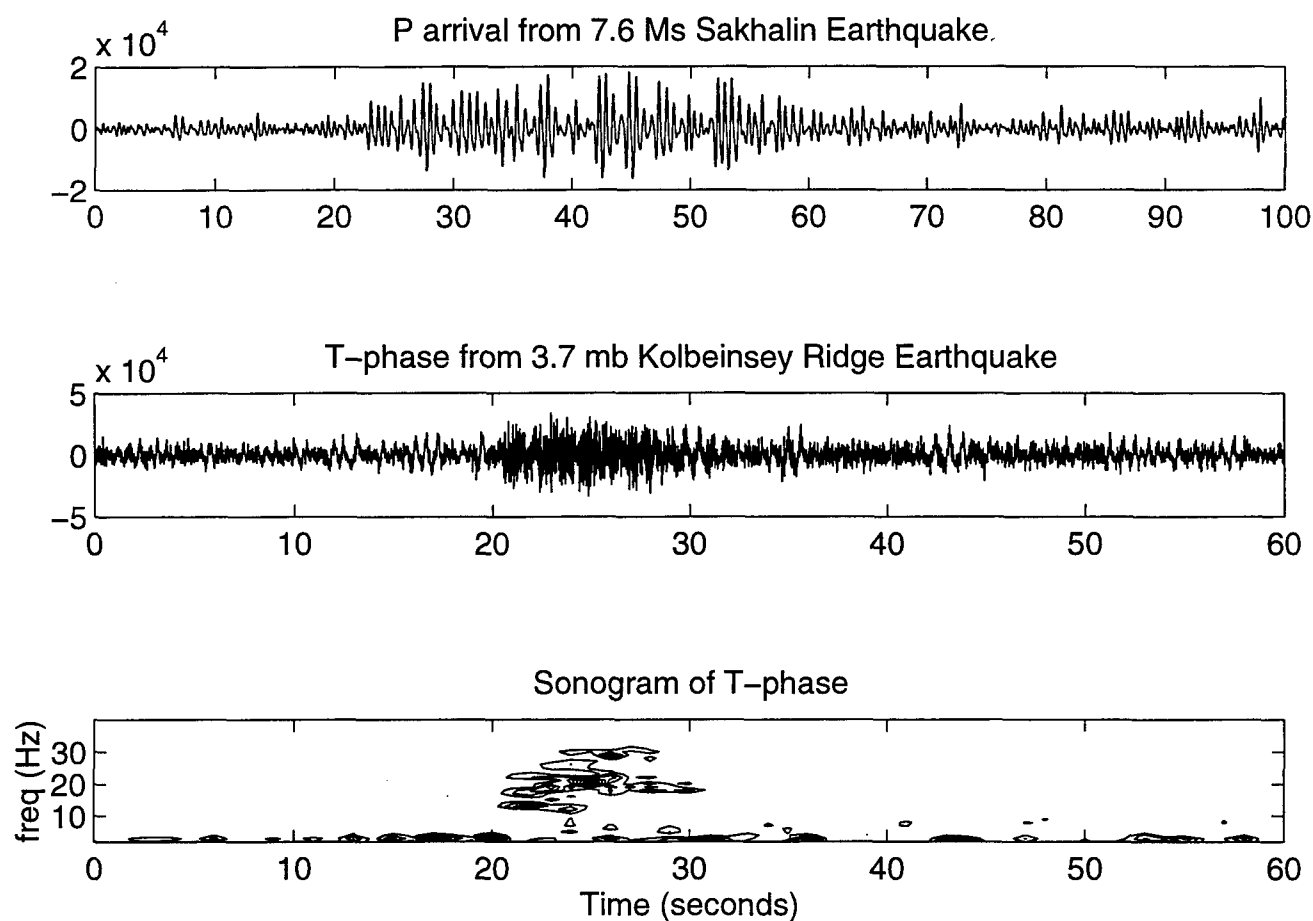
Figure 2. SOSUS hydrophone array data. Top: time series of beam data for a teleseismic event (range 50–60 degrees). Data have been filtered (2nd order Butterworth, pass band 1–4Hz). Lower two panels: T–wave from regional event Time series is low–pass filtered (5th order Butterworth, cutoff 40Hz). Time window for spectral estimate in sonogram is 1 second.

Mohns Ridge Activity Nov/Dec 1995

Land-Recorded Events
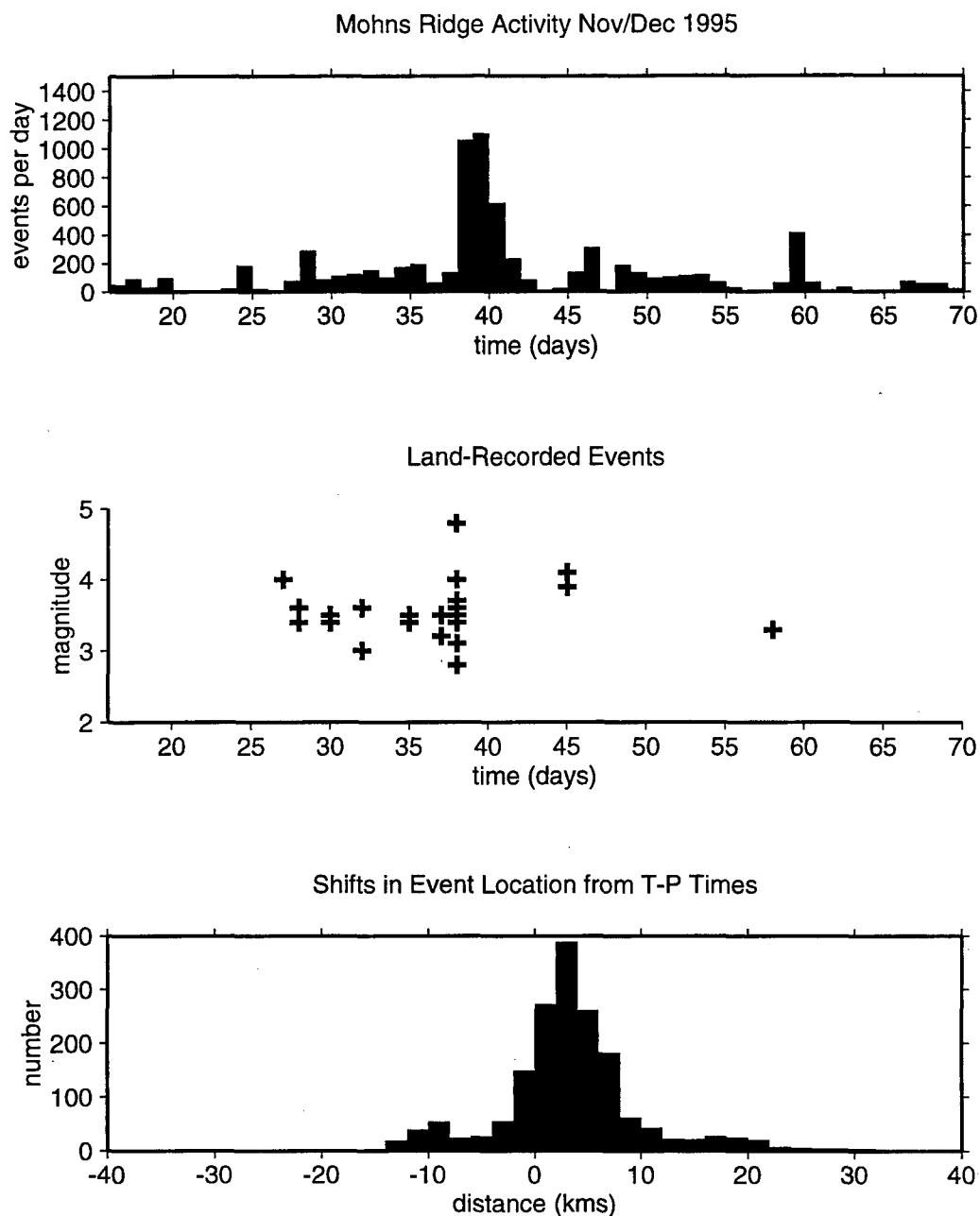
Shifts in Event Location from T-P Times

Figure 3. Temporal and spatial distribution of events that occurred during the earthquake swarm on the Mohns Ridge Nov-Dec, 1995. 3a) Top panel shows number of events recorded by SOSUS hydrophone arrays during the swarm. Day 20 corresponds to November 20, 1995. Greatest activity was recorded on Days 38-41 (Dec 8-11). The level of background activity is well below that shown for this time period. 3b) Middle panel shows events listed by CMR and their magnitudes (mb). 3c) Bottom panel shows the relative shifts in SOSUS-recorded events, with respect to a land-derived master event, based on P-T arrival time differences. Most events occur within a single region but two small populations are evident 10-20km either side of the master event location.
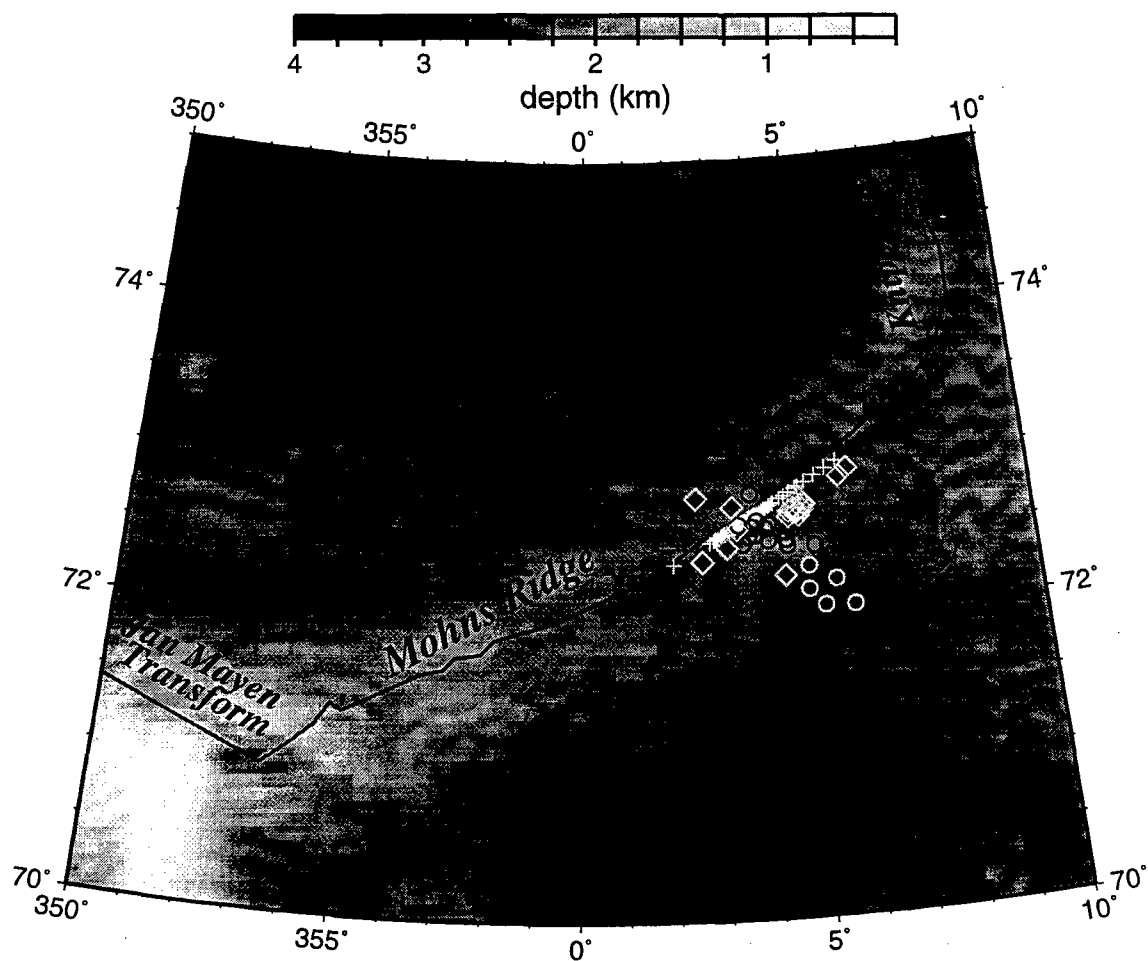
Figure 4. Epicenter estimates for the Mohns Ridge swarm of earthquakes. Land-derived epicenters for the main swarm (nov-Dec95) are shown by 'o'; light o's are locations ruled out by SOSUS analysis. Diamonds show land-derived events that occurred in the year following the main swarm. White crosses are location estimates based on SOSUS P-T arrival time differences and projection of the shift distance, relative to a master event, onto the trend of the ridge axis.